Evaluating Sustainable Interaction Design of Digital Services: The Case of YouTube

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ABSTRACT

Recent research has advocated for a broader conception of evaluation for Sustainable HCI (SHCI), using interdisciplinary insights and methods. In this paper, we put this into practice to conduct an evaluation of Sustainable Interaction Design (SID) of digital services. We explore how SID can contribute to corporate greenhouse gas (GHG) reduction strategies. We show how a Digital Service Provider (DSP) might incorporate SID into their design process and quantitatively evaluate a specific SID intervention by combining user analytics data with environmental life cycle assessment. We illustrate this by considering YouTube. Replacing user analytics data with aggregate estimates from publicly available sources, we estimate emissions associated with the deployment of YouTube to be approximately 10MtCO_2e p.a. We estimate emissions reductions enabled through the use of an SID intervention from prior literature to be approximately 300KtCO_2e p.a., and demonstrate that this is significant when considered alongside other emissions reduction interventions used by DSPs.

CCS CONCEPTS

• **Human-centered computing → HCI design and evaluation methods**; • **Social and professional topics → Sustainability**;

KEYWORDS

evaluation; sustainability; sustainable HCI; interaction design; digital service

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1 INTRODUCTION

Both the difficulty and importance of evaluation within Sustainable HCI (SHCI) has been recognised in recent years. A number of works [10, 50] have highlighted the sparsity of evaluation that has taken place in SHCI and the importance of developing appropriate methods. Researchers have developed frameworks and taxonomies identifying different criteria for evaluating the sustainability impacts of SHCI research [9, 31, 48, 58]. Recently, a promising model to elicit appropriate evaluation methods for specific SHCI research has been offered by Remy et al. [47], and it is notable in that it encourages both breadth of perspective and appropriate focus to allow rigour. It encourages evaluation which is pluralistic, interdisciplinary and considers the effects of a potential intervention from different scales.

This paper offers a detailed case study of evaluation that puts this model into practice. We apply it to one specific subfield within SHCI—the application of Sustainable Interaction Design (SID) to understand and reduce the environmental impact of digital services. Through doing this, we:

- Demonstrate the greenhouse gas (GHG) emissions reporting standards currently used by technology companies do not incorporate the delivery and use of digital services, and that this can act as a barrier to the uptake of SID techniques.
- Provide a method by which designers of digital services can evaluate the impact of design decisions on GHG emissions, and assess the value of SID proposals.
- Simulate the application of this to YouTube as an example digital service. By doing so, we demonstrate that emissions associated with digital services of this scale are sufficiently large to be worthy of consideration. We also demonstrate emissions reductions enabled by one SID intervention are of comparable scale to other

mitigation measures used by digital technology companies, such as the use of renewable energy to power data centres.

2 RELATED WORK

Sustainable Interaction Design and Sustainable HCI

The concept of Sustainable Interaction Design (SID) was first introduced by Blevis [5], who provided a rubric to integrate considerations of sustainability into the design of digital products and to critically evaluate existing designs. This stimulated broader research on *Sustainable HCI,* which is characterised [10, 33] as including both *Sustainability in Design* and *Sustainability through Design.* Sustainability through Design uses HCI approaches to address broader sustainability challenges. Examples include eco-feedback techniques [16] and social networks [13, 32] to reduce an individual's resource use; using mobile support for transport [15]; the use of crowdsourcing to support pro-environmental community activism [34]; using thermal imaging to encourage improved building efficiency [36]; energy-efficient retrofitting [35]; and support for last-mile logistics [4].

Sustainability in Design

Sustainability in Design research may also be subdivided broadly into two—that focused on improving sustainability of physical digital products (such as smartphones) and that focused on improving sustainability of digital services. The former has focused primarily on the issue of material use and waste reduction associated with interactive devices. It has studied people's attitudes and practices with regard to mobile technology to guide design in this direction [19, 22] and focused in particular on encouraging device longevity [49] through encouraging users to keep them for longer [39, 41]; the re-using of old devices by passing them on to others [19, 23]; repurposing them in different ways [23, 39]; and reusing their subcomponents [24].

Sustainability in Design of digital services, however, has focused primarily on energy use and associated GHG emissions of systems of products and infrastructure associated with service use. Some of this work takes a practice-centric perspective, exploring the variety of practices an individual user develops around the digital services they use and the environmental impact this has. This includes exploring practices associated with tablets [30], mobile devices [64], and larger configurations of equipment [3]. Other work takes a more systems perspective, including exploring the long-term increase in energy use by the internet that results from current trends in user behaviour [20, 44], and extending the SID rubric of Blevis to apply to the design of digital services [43].

This body of work contains a number of proposed interventions to reduce the environmental impact of digital services. These include identifying and eliminating *digital waste* [44] such as the practice of using video streaming in the background as an audio source [30], "nudging" users to lower fidelity data streams [43], using locally stored content to reduce streaming at peak times [64], and many others. In this paper, we use an intervention based on one of these (video streaming in the background) to concretely illustrate our proposed approach to assessment and to demonstrate the potential value of SID insights. The approach we use can be applied to many more of these interventions, subject to the availability of appropriate usage data.

Life Cycle Assessment and Digital Technology

Within our evaluation, we use life cycle assessment (LCA) [59]. This has been proposed as a promising method for the evaluation of SID [47]. Within the environmental assessment literature, LCA approaches have been used to assess digital services [56, 63] and the impacts of alternate design decisions [55]. Within SHCI, it has been combined with Ubicomp techniques to estimate the carbon footprint of cooking patterns [8]. It has been used in simplified form to assess SID interventions [3], and to assess approaches to moderating the energy impacts of long-term growth in data demand [20, 44]. The research we present in this paper can be considered as building on this work by enriching the LCA method with sufficient detail to assess SID interventions more accurately, and showing how and why such assessments can integrate with the wider corporate GHG strategy of digital service providers.

3 EVALUATION APPROACH

Our evaluation of Sustainable Interaction Design of digital services draws inspiration from Remy et al.'s model [47]. They advocate that such an evaluation should consider *goal*, *mechanism*, *metric*, *method*, and *scope*.

The *goal* of the body of research outlined above is to reduce the environmental impact of digital service provision. In this paper, we focus our *scope* specifically on the reduction of GHG emissions associated with service use.

Remy et al. [47] encourage the consideration of the broader sociotechnical *mechanisms* which will influence and be influenced by the intervention to be evaluated. In this paper, we consider two such mechanisms: (i) at the level of the political economy and corporation, we consider corporate GHG strategies of technology companies and the factors which shape them;[1] (ii) at the intra-corporation level, we consider

[1] What we are doing for the corporate sector is analogous to the work of Thomas et al. [60] for the public sector.

design practice within technology companies which design and deploy digital services.

At the first level, we analyse the factors which shape corporate GHG strategy and look in detail at the associated corporate reporting standards. We show how the current standards incentivise progressive companies to integrate green design principles into physical products, but not digital services. We identify what changes would be necessary to make this happen.

At the second level, we provide a *method* which allows the designer of a digital service to combine user and digital systems analytics data and participatory approaches with environmental LCA techniques to quantify GHG emissions associated with that service. We show how it can be used to assess the role of SID interventions in reducing such emissions. Quantifying such reductions therefore provides our *metric* .

Widening the *scope* to considering how to influence the stakeholders in the system to make changes to practice, the method we are employing could be considered examples of "projective validity" [51] and "impact ripples" [28]. We are attempting to simulate the emissions reductions enabled by a potential SID intervention in the future, and through doing so catalyse a discussion among stakeholders regarding the value of improving corporate reporting and design practices in the ways we propose.

We close our analysis with a further widening of the *scope*, and give a brief overview of the limitations of our described approach within current socioeconomic practice, and discuss how and why it could be applied to incorporate an explicit recognition of limits to GHG emissions.

4 THE ROLE OF SUSTAINABLE INTERACTION DESIGN IN CORPORATE GREENHOUSE GAS STRATEGY

We now discuss how SID can be effectively incorporated into corporate GHG strategy of Digital Service Providers (DSPs). We firstly consider the structure of such a strategy, including how emissions are quantified, and how this applies to DSPs. We then show how consideration of such emissions can be incorporated into the design and ongoing development of a digital service and how potential SID insights and interventions can be evaluated.

Corporate GHG Strategy

With the rise in awareness of the magnitude of the challenge that climate change presents humanity and the global ecosystem, there has been increasing pressure from diverse stakeholders on companies to address this challenge as part of their business operations. Notably, institutional investors have recognised that the potential impacts of climate change and a transition to a low-carbon economy will have disruptive effects. These present both risks and opportunities to a company's activity, and to the broader economy. It is in the interests of an institutional investor to encourage action on climate change by the companies in which it invests for two reasons: (i) to understand the (financial) risks and opportunities an individual company faces as a consequence, and so take this into account in investment decisions; (ii) to encourage action by the private sector more broadly, and to reduce risks to the market (and wider society/ecosystems) from unabated climate change.

CDP (formerly the Carbon Disclosure Project) [6] is a global non-governmental organisation which uses the power of these large scale investors to encourage such action by companies. It encourages transparency and standard approaches to the assessment and reporting of climate strategy. At the core of such a strategy is a commitment to reduce GHG emissions. The approach taken is to *understand* the different sources of GHG emissions its activities contribute to, *quantify* how impactful they are using a well-defined and verifiable methodology, set *targets* for emissions reduction, and create different kinds of initiatives to *reduce* emissions in line with these targets. Companies that submit a CDP climate change response each year give details of this in a standardised way. They also report on their climate change governance, strategy, policy engagement, low carbon products, and emissions reduction initiatives, as well as risks and opportunities that the business is exposed to in relation to climate change and the move to a low carbon economy. Over 6300 companies responded in 2017, representing over 20% of global emissions, and many of these agreed for their responses to be publicly available.

Quantifying and Reducing Greenhouse Gas Emissions

A core aspect of corporate climate change strategy is the quantification of GHG emissions resulting from the activities of the company, and the commitment to reduce them over time through different emissions reductions initiatives. We now consider this process in more detail, with particular reference to DSPs. We argue that the current methodology is inadequate with respect to such companies. Furthermore, we argue that expanding the methodology to account for emissions from the broader digital infrastructure will provide opportunities for SID to make contributions to reducing GHG emissions.

Quantification of emissions resulting from a company's activities uses a methodology defined in the Greenhouse Gas Protocol [66] and presents results in terms of the global warming potential over a period of 100 years (GWP_{100}), specified as *tonnes of carbon dioxide equivalent* (tCO_2e).

A core question that needs to be answered in such reporting is: where is the boundary of a company's activities with respect to such reporting? The GHG protocol responds to this by defining three 'scopes' of emissions reporting. Scope 1 and 2 emissions are those that result from the direct activities of the company, often defined as those facilities which the company has operational control of. Within this, Scope 1 emissions are those which result from a company's activities which directly emit GHGs into the atmosphere—such as a vehicle delivery fleet, an on-site diesel generator, or the release of CF_4 gases during the manufacture of integrated circuits. Scope 2 emissions are those that result from a company's purchase of steam, heat/cooling, and (often most significantly) electricity from a grid. Scope 3 emissions are defined in the GHG protocol as "All indirect emissions (not included in Scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions."([65]) These are emissions resulting from a company's activities, but are outside the direct operational control of the company (i.e. they are Scope 1 or 2 emissions for another company or individual). The boundary of Scope 3 emissions is less well-defined than Scopes 1 and 2. These can include emissions such as business travel; subcontractors manufacturing devices for the company to sell or use in assembly; hosting of datacentre services with a cloud provider; third-party transportation and distribution of a product to a customer; use of products by a customer and their final disposal / recycling. Scope 3 reporting, unlike Scopes 1 and 2, is not yet a mandatory part of environmental reporting. The motivation for such Scope 3 reporting is that, even though the company is not *directly* responsible for these emissions, its policies and decisions have an *effect* on them. Hence it can influence and potentially reduce them. For example, a tech company can (i) require its suppliers of bespoke integrated circuits to effectively capture CF_4 emissions during their manufacture; (ii) opt to minimise the use of aviation in product distribution; or (iii) design their products to be more easily disassembled and work with recycling companies to extract rare earth metals to reduce the emissions from their mining.

One category of Scope 3 emissions of particular relevance to HCI is "Use of Sold Products." The GHG Protocol states that:

"If fossil fuel or electricity is required to use the company's products, product use phase emissions may be a relevant category to report. This may be especially important if the company can influence product design attributes (e.g. energy efficiency) or customer behavior in ways that reduce GHG emissions during the use of the products."

For digital products and services, such influencing of product design attributes and customer behaviour is exactly what HCI research is about. Scope 3 understanding and reporting of such emissions hence has the potential to harness research insights and results from "Sustainability in Design." If proposed interventions emerging from this body of work can be demonstrated to have a significant potential to reduce such emissions, then there is greater potential for them to impact design practice within technology companies.

For software and digital services, there is an additional barrier to be overcome: Scope 3 guidance assumes a discrete physical product, such as a TV or a car. It does not provide guidance as to whether and how to report emissions associated with distribution and use of a digital service. Hence, from the perspective of the GHG Protocol, such emissions need not currently be considered. As a consequence, providers of digital services do not report these as part of their Scope 3. Alphabet (Google), for example, note in their 2016 CDP response [1] that "We have minimal downstream transportation and distribution activities, given that our business involves minimal physical delivery of any products or services. As a result, any associated emissions are *de minimis* in size." Likewise, they comment, "Given the small size of our product portfolio, emissions associated with use of sold products are expected to be *de minimis* relative to our overall footprint."

Nonetheless, the downstream corporate value chain associated with such services clearly results in GHG emissions: the energy used by network equipment, caches, and end user devices to access and use the service.[2] For a provider of digital services, such emissions can be a significant part of their Scope 3 corporate emissions. Design decisions can therefore have a notable impact on their size. For this reason, we believe that the GHG Protocol should be enhanced to encourage reporting of Scope 3 emissions associated with delivery and consumption of digital services, and to provide a standard way of doing so.

5 INTEGRATING SID INTO DIGITAL SERVICE DESIGN

Many technology companies incorporate some element of "Green Design" or "Design for Environment" in their production of physical products [14]. We advocate that given emissions associated with digital services can also be significant, a similar approach should be applied to them. Insights and principles from Sustainable Interaction Design would form a key part of this. Such an approach could include the following aspects:

- Analysis of potential and actual practices emerging in the user community, such as that conducted by Lord et

[2] It is possible that some distribution emissions are reported in the Scope 3 category of "purchased goods and services," as Alphabet provides no information regarding what this includes.

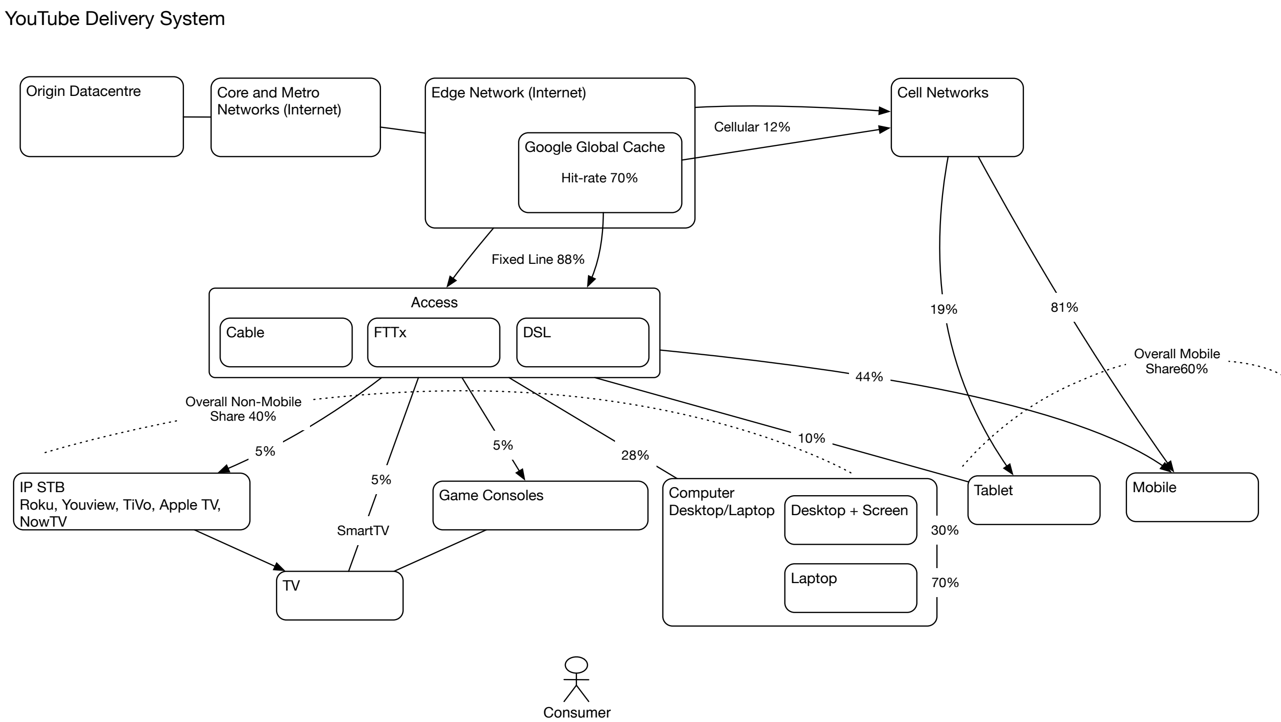

Figure 1: Process model of the service.

al. [30]. For new services, the use of personas (and anti-personas) [45] could be used to explore the diversity of practices which might emerge. Of particular interest is how users might subvert (intentionally or not) the intended usage.

- Models of anticipated user behaviour, or actual behaviour derived from user analytics data. This should quantify the number of users, and the ways in which they use the service. Ideally these would be linked with different (actual or potential) practices by identifying associated "behavioural footprints" for these practices which can be observed in user analytics data. Such models can also be scenarios which consider anticipated growth or change in the way the service is used, such as the spread of a practice through a user community.
- A process model of the service, using Environmental LCA techniques, allowing emissions associated with service use to be estimated for a given user behaviour model.
- Assessment, using these elements, of the impact on GHG emissions of alternate design decisions and interventions. This can be fed into the wider decision-making process regarding design, deployment and enhancement of the digital service.
- Incorporation of Participatory Design principles in such a decision-making process. A community of users could be involved in proposing potential alternate design options and interventions, based on reflection of their own practices. They also could be involved in assessing such options. By offering them a way of understanding the impact on GHG emissions of rolling a feature out globally, they will be able to play a more informed role in decisions as to whether it is worth it, from the user perspective.

We now consider how this might work in more detail for a given digital service. We illustrate this through analysis of YouTube. We consider the specific user practice identified by Lord et al. [30] of using YouTube as an audio source, and hence the unnecessary "digital waste" [44] of video content. We estimate the overall GHG emissions associated with

YouTube use over a period of a year (2016). We also estimate the reductions enabled by designing to account for the practice described above and eliminating unnecessary digital waste.

At each stage, we discuss how user analytics data can be used to identify the key parameters necessary for estimating emissions. Though there will be some variation, much of what we discuss will apply to most digital services with user analytics capability. We use YouTube as an illustrative example to make the general process clear.

6 SIMULATING THIS IN PRACTICE: YOUTUBE

Google (Alphabet) is considered one of the most progressive major companies with regards to its climate change strategy, receiving an "A" rating from both CDP [1] and Greenpeace [18]. Its initiatives have included:

- The development of approaches to significantly decrease datacentre energy overheads, and sharing many of their insights freely with others.
- A commitment to move to 100% purchasing of renewable energy. Much of this is purchased through long-term agreements, allowing suppliers to make additional investment.
- Investments in renewable energy technology startups.
- Lobbying in favour of GHG emissions reductions and publicly resigning from trade bodies that promote climate denial.

It is a good example of a company with a "Strategically Proactive" approach [11] to climate change, and so is likely to be open to ways in which to further improve its performance in this respect. We now demonstrate that expanding Scope 3 to include digital distribution, and integrating sustainability into the design of its digital products through SID, offers one such way.

Estimating GHG Emissions Associated with YouTube Delivery

We now estimate Scope 3 GHG emissions associated with YouTube delivery, and then assess the reductions enabled by our chosen SID intervention.

Method

We conduct a scoping LCA of YouTube delivery and viewing to give an estimate of electricity used globally for YouTube over a period of a year (2016). Inevitably, this will be an estimate and will be less accurate than would be available to Google internally. Effectively, we simulate a simplified form of what an interaction designer at YouTube interested in evaluating the SHCI intervention could do. They would have user analytics data to gain a detailed understanding of the diverse behaviours exhibited online, geographical distribution of audience etc., and also detailed monitoring data from their datacentres regarding power use, volume of data served etc. Although we do not have this level of detail, it can be approximated based on publicly available data and analyst estimates about YouTube usage, and secondary data from other sources.

The method for evaluation we adopt is a modified form of the LCA methodology as described in ISO standard 14040 [59]. Following this standard, we adopt a process-based approach to LCA—modelling the processes involved in the provision of a given service and allocating the environmental burdens appropriate for a given quantity of service delivered—in our case, the total service delivered worldwide by YouTube during 2016. We present results in terms of energy used and associated global warming potential in terms of tonnes of carbon dioxide equivalent (colloquially known as the "carbon footprint").

We exclude emissions associated with the manufacture of the devices and equipment used in the delivery process. Such impacts would not form part of Scope 3 climate reporting, and are outside the scope of what the software service design can typically influence ([25], p201).[3] For similar reasons, we do not consider impacts associated with the creation and editing of the video content which is uploaded to YouTube. Given the goal of this assessment—to support Scope 3 reporting of digital services, and to assess the potential impact of design interventions in reducing the reported greenhouse gas emissions—we are justified in considering these outside the boundary of our system of study.

Based on the relative frequency of upload vs viewing, impacts of uploading are around 0.1% that of viewing and so below the 1% considered acceptable within LCA methodology for "cut off." Hence we also disregard upload as being negligible though it is technically within scope. For a digital service where this is not the case, techniques described below can also be applied to assess upload.

The system to be assessed is pictured in Figure 1. Much of the process model and the data supporting it are general, and so can be applied to analysing a variety of digital services. It needs to be parameterised with the data that is specific to the service being analysed and the (modelled or observed) pattern of usage—in our case, for YouTube in 2016.

We now give a description of each element of the system under study, what data is necessary to assess it, where such data could be obtained by a digital service provider, and what data we have used as a proxy for this. A full list of

[3] Though we note that choices and innovations made in service design can encourage the purchase of new or additional home equipment, as discussed elsewhere [43].

the data values used, and their sources, is provided in the accompanying materials to this paper.

Origin Datacentres and Google Global Cache. Any request for content goes to a datacentre that generates a response to coordinate delivery of the requested service. The central datacentres are also where the software platform development, video content transcoding and other ancillary services such as search, rating, discussion etc. take place. Much of the video content is delivered from a cached copy more local to the user to provide improved service quality. Systems carrying out this function are known as Content Delivery Networks (CDN). Google has its own, the Google Global Cache, which is used for the delivery of YouTube videos. It is straightforward for a company to monitor the energy used and the quantity of data downloaded by these data centres.

To estimate this, we use data made public by Netflix [38] regarding their energy used both by the central data centres and their CDN (Open Connect). We scale this relative to the data volume served by YouTube.

Service Use. A DSP would have access to detailed user analytics data regarding how and how much of a service is used. For our estimate of YouTube, we use as a central input the total number of hours of video content consumed, which was reported to be 1 billion hours per day for 2016. We estimate the average bitrate of YouTube services within the internet based on Cisco's estimate of global internet traffic [7], and SandVine's estimate of YouTube share for North America [52]. The resulting bitrate of 1.18Mb/s is comparable to that of the lowest resolution encoding of YouTube [17] so can be considered a conservative lower bound. It is used to determine the overall data volume of the service.

Core and Edge Network. The data from the Content Delivery Network needs to be transferred over "the internet"—specifically the core and edge networks consisting of fibre optic cables, hubs, switches, routers, and repeaters. It has been shown that the use of CDNs makes the length of such a journey relatively predictable [54], and estimates of the amount of energy involved in the core and edge network to transfer a certain quantity of data have moved towards a consensus figure. We adopt a figure determined by a survey of this work [53].

Residential Access Networks. Different technologies are used to transfer the data "the last mile" from an Internet Service Provider's (ISP) edge network to the home, and then within the home through WiFi. We calculate the energy impact of this access equipment by using power and usage data for representative samples of such equipment [29], and use this to calculate the energy required per user-hour of service. Different fixed access network technologies (DSL, cable and fibre) have different energy usage characteristics. A service provider can use user analytics data (specifically IP addresses) to determine which ISP and the corresponding technology a given residential user is connected with, and therefore the time each technology is used by their service. As we do not have access to this data for YouTube, we estimate the share of use of each access network technology based on their residential share according to OECD data [40].

Cellular Networks. A significant amount of service use takes place over the mobile network. A DSP has user analytics data—and in particular IP address and connection speed—which can be used to determine which users are connecting over mobile networks, what the data volume they consume is, and whether they are using 3G or 4G technology. To estimate this for YouTube, we use public data from CISCO regarding the total data volume over cellular networks, and data from Ericsson on the proportion of YouTube views over the mobile network in 2016. To allocate shares between 3G and 4G, we use a figure drawn from the 2016 global breakdown between the two technologies from the Ericsson Mobility Report [12], and UK Ofcom figures for the relative data share transmitted over each.

We use data from Andrae and Edler [2] with regard to the average energy expended per unit of data transferred over 3G and 4G mobile networks. Cellular intensities are significantly larger than fixed line networks.

End User Devices. A digital service can be used on a range of end-user devices. In the case of YouTube, it is accessed on mobile devices such as phones and tablets, through laptop and desktop computers, and through TVs—either Smart TVs, or by using IP set-top boxes/games consoles to provide internet access. We use data from EnergyStar reports and product data sheets to determine the power consumption of these devices. A DSP would be able to determine how much each different device type is used from their user analytics data.[4] To estimate this in our study, we use data from two sources. We use publicly available data from YouTube regarding the breakdown between fixed and mobile devices. To give a more detailed breakdown into specific device types, we combine this with coarse estimates made based on a review of public data reported by digital service providers and individual YouTube posters. The proportions used are given in Figure 1.

Assessing the value of the SID intervention. The specific SID intervention we wish to assess requires us to identify when users are using a video for audio only. While this will often be for music, it may not always be so. A heuristic for identifying this using analytics would be to note when the relevant browser tab is running in the background [43].

[4] For the purposes of this study, we ignore emissions associated with periods that home equipment is on but idle.

The prevalence of this practice is unknown and difficult to estimate without analytics data, but anecdotal evidence suggests it is widespread. For example, the most popular 'how to' video offering workarounds to make it easier to play YouTube in the background on mobile devices has over 4M views [62].

For our study, we adopt a conservative approach and consider only music videos. Given the uncertainty around actual numbers engaged in this practice, we consider three different scenarios regarding the prevalence among users. In the most conservative scenario, we assume 10% of music content is used audio-only. The second assumes 25% and the third, 50%.

We estimate the proportion of YouTube viewing associated with music videos using data from analysis performed by Pex.com, which found that the Music category was responsible for 27% of all views [61]. To determine reduction in data flow when only audio is streamed, we assume the audio-only content is streamed at a similar rate to that of Spotify's default of 160Kbps.

From Electricity Use to GHG Emissions. A DSP would have access to a regional and country breakdown of service usage around the world, and so could identify how much electricity is being used to deliver and use the service in each region/country. This can be combined with appropriate emissions factors for electricity generation in each region/country to determine associated GHG emissions. As we do not have such a regional breakdown of usage for YouTube, we estimate associated GHG emissions using the 2016 world emissions factor associated with electricity generation from the International Energy Agency for all activities except Google's datacentres (including Google Global Cache). These we assume are powered by renewable energy through purchase agreements and so, based on Google's CDP disclosure, we use an emissions factor of 0.

Results

Figure 2 presents our estimate of electricity usage associated with YouTube use in 2016, broken down into the main system components. Total electricity used is estimated to be 19.6 TWh, with associated GHG emissions of 10.1 $MtCO_2e$—-roughly comparable to emissions of an urban area such as Greater Glasgow, Frankfurt, Quito, or Providence [37]. This includes the savings of 116 $KtCO_2e$ from Google's existing purchasing of 100% renewable energy for datacentre activities. Under our three scenarios (10%, 25%, and 50%) for audio-only streaming of music, we find it enables emissions savings of 117, 293, and 586 $KtCO_2e$, respectively.

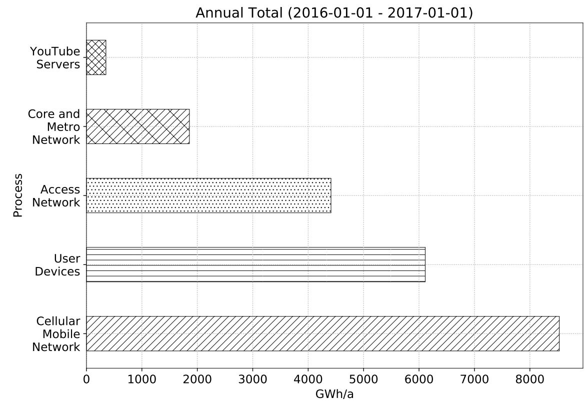

Figure 2: Estimate Energy Usage in delivering YouTube.

7 DISCUSSION AND LIMITATIONS

Through our analysis, we have shown that Sustainable Interaction Design, together with environmental LCA analysis, can be effectively incorporated into the design process of digital services. Our illustrative example of YouTube shows that the environmental impact of infrastructural use by a service can be substantial, supporting our argument that it should form part of a DSP's Scope 3 greenhouse gas reporting. This also corroborates the importance of considering the environmental impacts of infrastructure use when designing digital services, as advocated by Preist et al. [43]. By considering the whole end-to-end system involved in the delivery of a digital service, we avoid the risk of optimising a single process within it at the expense of increased emissions elsewhere.

Our example analysis of one straightforward SID intervention estimates that the emissions savings it enables are between 1% and 5% of the total emissions. This is comparable in scale to the existing reductions obtained by Google's purchase of renewable energy to power YouTube's servers. Hence, such reductions are sufficiently large to be worthy of consideration by DSPs.

Further research, ideally in partnership with DSPs, is necessary to apply further insights of SID to digital services, identify new intervention opportunities, and quantify their value through the use of user analytics data and life cycle assessment.

Limitation 1: GHG Accounting, or Real Reductions in Emissions?

If the reductions our intervention enables are to be realised, a further step is needed. Reducing flying by the employees of a company will reduce its reported Scope 3 GHG emissions, but will only reduce actual emissions if enough do this to result in an actual reduction in plane flights (as opposed to the same number of flights carrying slightly fewer people). Similarly, reducing data over networks (and in particular mobile networks) may simply result in the network being used less efficiently while still using the same amount of energy to keep it operational. However, for large digital services such as YouTube, the reductions we are discussing are substantial. They will lead to some reductions in energy use in the cellular network from current adaptive techniques such as powering down parts of mobile cells when demand is low. They will also reduce anticipated peak demand, which could allow a sparser network to be deployed. However, for the enabled reductions to be fully realised will require the deployment of newer energy optimisation techniques in mobile cell management, such as optimally combining adaptive antenna and DTX micro-sleep strategies [21].

Limitation 2: Energy Use of a Single Service

The analysis described in this paper has its scope defined through reference to the Scope 3 GHG reporting guidelines. As such, it does not include emissions associated with the manufacture and deployment of the infrastructure on which the service runs, and does not consider the environmental impacts beyond global warming, induced by the manufacture and end-of-life of this infrastructure. It also does not consider the consequential impact of increased service use driving demand for increased infrastructure deployment. A more full analysis of the impacts induced by a digital service would account for these wider issues. Furthermore, services are not deployed in isolation: they interact with each other as part of a broader ecosystem with one potentially encouraging the use of others. The design of one service is likely to have an effect on usage and emissions of others which interact with it, even though these are owned and managed by different organisations. Quantifying and mitigating the impact of such interactions in the design process is likely to require collaboration between companies, and is an opportunity for further work.

Limitation 3: Rebound and Rising Demand

The example we have described here, in line with much of corporate “Design for Environment”, can be characterised as “eco-efficiency”: design to eliminate unnecessary waste and so reduce associated emissions. Such an approach rightly draws criticism [26, 27, 46] for several reasons.

Firstly, it is well known that such an approach can result in the *rebound effect*: the increased efficiency will result in a reduction in price of the associated service, and therefore increased use because it is cheaper. In our particular case, this would manifest as increased use of YouTube, particularly over the mobile network, because the reduced data required would mean that the data cost (or more likely, the likelihood of reaching data limits on mobile contracts) has been reduced.

However, this effect is likely to be dwarfed by other factors resulting in rapid growth in overall usage of video over the internet (both from YouTube and other providers). The “reductions” we have discussed would simply result in a decrease in the rate of growth of energy use and associated emissions, not an absolute reduction. Currently, both computation and bandwidth are sufficiently cheap and readily available in many situations that they are often considered as a limitless resource for designers under the “Cornucopian Paradigm” [43].

Beyond Eco-Efficiency: A Limits Perspective

However, the broader approach described in this paper can also be applied to a more radical, limits-based perspective [42] on design of digital services, should a DSP be willing. A company (or sector) could adopt an upper bound to the energy and/or GHG emissions its services can “use” in a given year. The approach to green design of digital services described in this paper would then be able to determine for different scenarios whether such a limit would be respected. It could also assess the role of different SID techniques involving persuasive design and choice editing applied to digital services [43] in helping meet the limits. When the service is deployed, user analytics would allow the ongoing monitoring of the service and real-time assessment of its environmental impact. If this suggests that chosen limits might be breached, then pre-selected SID techniques could be deployed responsively and potentially automatically to reduce energy and emissions.

The idea of a company adopting such a perspective may seem radical and a way off. However, there are signs of thinking in this direction. A number of companies are adopting “science-based targets” for their overall emissions [57]. This means they adopt ambitious reductions in line with the scientific consensus as to their share of what is necessary to keep anthropogenic GHG warming below 2°C. As the impacts of climate change bite further and the scientific consensus on what is necessary becomes even clearer, it is likely that initiatives such as this will become both stronger in what they expect of companies, and more widely adopted by companies and sectors. Should this happen, the approach described in this paper can support DSPs in designing their services to meet their moral obligations to work within such limits.

8 CONCLUSION AND FUTURE DIRECTIONS

By evaluating the role of SID applied to digital services, we have (i) identified the need to alter GHG emissions reporting standards of technology companies to incorporate the delivery and use of digital services, and demonstrated that emissions associated with this can be significant; (ii) shown how designers of digital services can evaluate the impact of design decisions on GHG emissions, and assess the value of SID proposals; (iii) simulated the application of this to YouTube as an example digital service and demonstrated that emissions reductions associated with one SID intervention are likely to be significant. Through doing so, we have demonstrated both the value of SID for GHG emissions reduction, but also the value of applying “evaluation beyond usability” to sustainable HCI [47].

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